5. LIGHTWEIGHT VEHICLE STRUCTURES

A. Lightweight Stainless Steel Bus Frame—Phase III

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Contract No.: 4000010114

Objectives

- Investigate and demonstrate the mass savings potential of ultra-high-strength stainless steel as applied to the structure and chassis of a full-size urban transit bus.
- Finalize design and analysis and build a full-scale prototype of the body structure and chassis.
- Investigate all of the fundamental feasibility issues related to the structure and chassis:
  1. Fabricate and test large lightweight stainless steel sandwich panels
  2. Fabricate roll-formed, high-strength stainless steel sections
  3. Test the feasibility of lightweight stainless steel cantilever seats
  4. Design and fabricate lightweight stainless steel independent suspension
  5. Integrate the traction motors into the suspension design

Approach

- Execute the basic body structure, including the floor and roof sandwich panels, pillar assemblies, longitudinal rails, and suspension subframes.
- Choose prototyping techniques that emulate the intended production process as closely as possible to aid in developing robust but cost-effective manufacturing techniques essential to meeting the objectives of the project.
- As computer-based design and analysis details of the bus develop, conduct hands-on physical experimentation in parallel to support the concepts and methods.

Accomplishments

- Completed building a specialized resistance welder for joining sandwich panel segments.
- Assembled the floor structure, including all floor sandwich panel segments and subframe subassemblies.
- Assembled the roof structure, including all roof sandwich panel segments.
- Produced a report documenting design enhancements for manufacturability.
- Produced and documented fixture strategy for main assembly.

- Completed assembly of primary structure.
- Fabricated and assembled window and doorframe components.
- Fabricated and assembled front and rear body end sheet metal components.
- Created computer-aided design (CAD) model for seat design.
- Conducted finite element analysis (FEA) for seat design.
- Produced a report documenting side impact analysis results.
- Performed a physical test of crash energy absorber tubes.
- Received delivery of traction motors, inverters, and inverter software (propulsion components)
- Modified design of suspension geometry for compatibility with new motor.
- Modified design of suspension components for compatibility with new motor.
- Provided support for independent cost analysis.

Future Direction

- Assemble closeout panels.
- Complete the fabrication and installation of suspension, steering, and spring components.
- Fabricate driver controls.
- Prototype two seats.
- Assemble propulsion components.
- Testing of structure.

Introduction

Advanced-technology transit bus concepts have made significant advancements in terms of low weight and fuel economy. However, these gains have come at the expense of higher manufacturing costs. In spite of attempts to use life-cycle costs to justify their purchase, initial cost remains a major obstacle to the introduction of fuel-efficient buses.

Autokinetics was approached by DOE for help with solving this problem. Specifically, Autokinetics was asked to develop concepts for a lightweight urban transit bus based on the use of high-strength stainless steel. In the passenger car field, Autokinetics had developed structural and manufacturing techniques for the cost-effective use of stainless steel in spaceframes and suspensions. DOE wanted to determine whether this approach could be applied to transit buses as well.

The program was structured in three phases:

- Phase I—Initial Concept Development
- Phase II—Concept Verification and Initial Design
- Phase III—Final Design and Prototyping of Body and Chassis

Phase I and Phase II have been successfully completed. Phase III will result in a full-size body structure and suspension that will be tested statically and dynamically. The development of an optimized hybrid powertrain and other vehicle systems will be addressed in a separate project.

This project was unusual in that no formal mass or cost targets were given. The object was to save as much mass and cost as possible.

Specialized Segment Welder

Preliminary welding tests indicate that the panel segments can be successfully joined together using resistance welding. This approach utilizes a joint configuration that reduces complexity and the need for extremely tight tolerances. To create a prototype, spot welds need to be placed along the nearly 8-ft seam between panel segments.

To accomplish this, a special spot-weld gun was required that could reach at least halfway across the floor and roof. The design of this welder was reported on previously. A special support and backup structure were fabricated and fitted with conventional transformer gun components. This arrangement is shown in Figure 1.

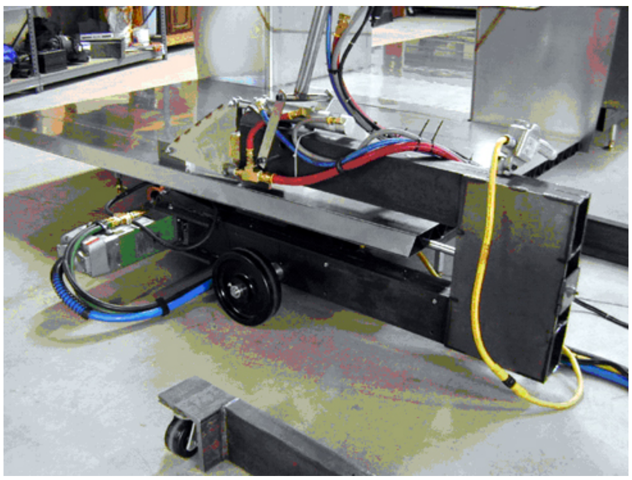

Figure 1. Specialized segment welder.

Special contact tips were also designed and fabricated to accommodate the slightly different configuration of the joint between the subframe and floor panel. As the joining of the panel segments progressed, the contact tips and the welding techniques were refined.

Floor, Roof and Primary Assembly

A major milestone was achieved as the primary body structure was assembled during this reporting period.

The primary structure framing sequence shown in Figure 2 consists of three main elements. First, the floor panel components, including subframes, are located on the framing platform and joined together forming a completed floor assembly.

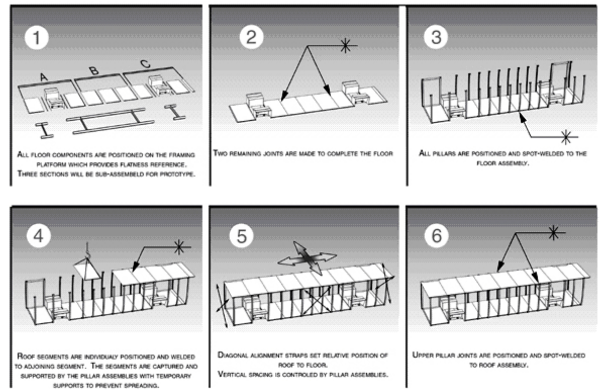

Figure 2. Primary structure framing sequence.

Next all side pillars and door frames are positioned and attached to the floor assembly. Positioning is controlled vertically by the floor, laterally by a taut wire running along the side, and longitudinally by a measured distance. The use of a simple temporary support aid maintains the pillar in a plumb orientation.

Finally, the roof segments are hoisted into position and brought to rest on the pillar brackets. At this point, all roof segments are joined, forming a completed roof assembly. The pillars are then attached to the roof in a similar manner as with the floor.

It was determined that a number of variations on this theme were possible. One such variation, to preassemble roof segments into three sub-assemblies, was used for the purposes of this prototype build. This reduced the amount of hoisting and overhead welding. Another was installing the door frames after the roof assembly was complete.

Relative position between roof and floor assemblies was monitored throughout this sequence and found to be virtually self-locating. Figure 3 is a photograph of the completed primary structure.

Figure 3. Primary structure.

Front and Rear End Sheet Metal

During this reporting, the sheet metal components, which close out the front and rear ends of the body, were fabricated and installed onto the primary structure. These components were fabricated to incorporate some design refinements for improved NVH (noise, vibration, and harshness) characteristics. For example, the lower edge of the rear window and front windshield apertures were reinforced, and the sheet gage of the seat pan, compartment bulkheads, and fascia was increased from .030 to .050 in. In Autokinetics' judgment, improved NVH qualities gained by these refinements more than offset the slight weight increase.

For prototype purposes, the large sheet components were fabricated in halves and joined along the vehicle centerline. This would not be necessary in series production.

Figures 4 and 5 are photographs of the completed body end sheet metal.

Figure 4. Rear end sheet metal.

Figure 5. Front end sheet metal.

Seat Design

Beginning with the initial passenger seat concept, a detailed design sufficient for prototyping was created. As shown in Figure 6, the design is a cantilevered type, which attaches by special brackets to two adjacent body pillars. On the seat side, each bracket is attached to a lateral beam. The arrangement is such that the brackets are rigid, movement-carrying connections. Therefore, vertical seat loads are transmitted into the pillar as bending loads.

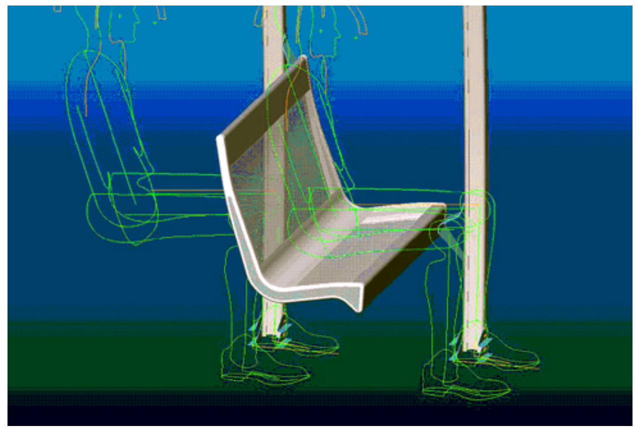

Figure 6. Front end sheet metal.

Completing the design are two L-shaped end caps connecting the lateral beams, and perforated sheet forming the seating surface. A reinforcement pan is attached between the end caps to control local flexing of the seating surface. The entire seat structure will be fabricated in stainless steel and is expected to be lightweight and durable and exhibit very little deflection under normal load.

An FEA model was constructed to verify load capacity and predict deflections. A proof load of 1500 lb was applied to represent a 3-g loading condition with two 250-lb passengers on the seat. The plot shown in Figure 7 indicates the material will remain below yield, while deflection (including pillar deflection) will be on the order of 1.75 in., measured vertically at the most inboard edge of the seat.

Crash Energy Management System

The crash energy management system, based on the principle of inverting stainless steel tubes to absorb crash energy, was described previously. During this reporting period, physical energy-absorbing (EA)) tubes were produced and tested.

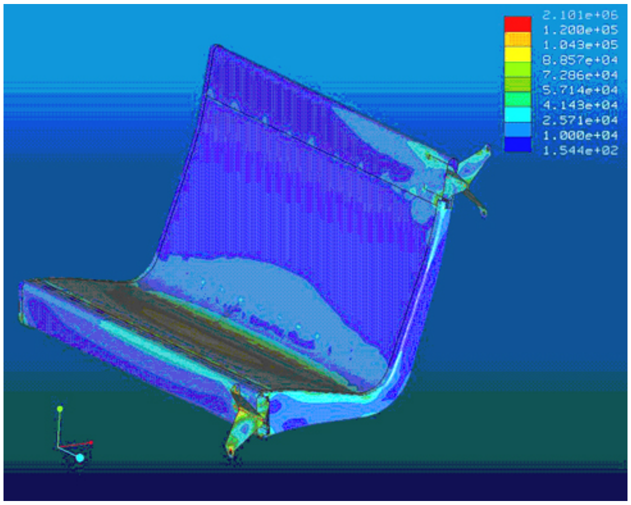

Figure 7. FEA model of passenger seat design.

Autokinetics has specially constructed a machine that applies a force axially to a given tube and measures that force in real time as the tube is worked into an inverted state. Several such EA tube tests were performed on the physical specimens and data were collected.

The tube inversion process inherently results in a very uniform, constant force. The level of this force can be set during design by adjusting certain parameters such as the diameter and wall thickness of the tube. A force level of about 12,000 lb per tube (there are 12 tubes in the front-end system) was chosen as the most appropriate for protecting the occupants of both the bus and the impacted vehicle.

The crash energy management system is well suited for a front-end and rear-end crash event. However, of particular concern for a "low-floor" bus is the side impact crash event. The cause for concern is the fact that bumper of the impacting vehicle will strike the bus several inches above the floor. As a result, the pillars must engage the impacting vehicle and carry the load into the floor without excessive intrusion (3 in. is allowed).

To address this concern, a linear FEA model (shown in Figure 8) was constructed to roughly predict load capacity and deflection. It was determined that reinforcement of the lower inside portion of the pillar would be required to manage the load satisfactorily. In addition, a bumper engagement rail was added along the exterior to ensure a distribution of the load application. With these modifications, model data were prepared and sent to Oak Ridge National Laboratory (ORNL) for a more refined nonlinear analysis capable of predicting deflection beyond the elastic range of the structure. The ORNL analysis, while promising, indicates that more spot welds will be required to prevent detachment of the pillar reinforcement. Other detail design changes may also be required to fully meet the requirement. Additional funding will be required for ORNL to complete this additional analysis.

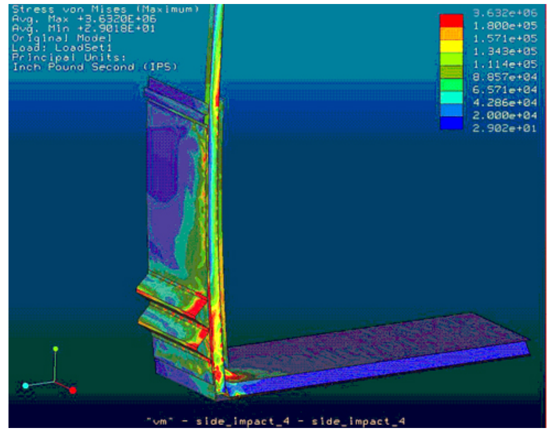

Figure 8. FEA model for side impact study.

Suspension /Driveline (New Motor)

With the vehicle body structure nearing completion, a greater emphasis has shifted to the suspension and driveline.

As reported previously, traction motors and controllers were ordered from PreMag; however, PreMag experienced difficulty in molding the stators and was unable to deliver the motors in a timely manner. Therefore, the decision was made to implement a contingency plan to pursue an alternate motor supplier.

Discussions were initiated with UQM. A motor currently being produced by UQM, the PowerPhase75, was identified as an appropriate selection. Recently developed technology allowing the power of the motor to be upgraded contributed to this decision. The first prototype bus will use the current PowerPhase75, with the intent to use the upgraded version in future buses.

Because the PowerPhase75 is physically different in size and shape from the PreMag motor, a study was conducted to identify any packaging issues. A number of "short-coupled" and hub-mounted concepts were explored. It was found that with some modification to the suspension design, the motors could be hub-mounted. This avoids considerable complexity associated with the short-coupled or right angle drive approach.

Given this information, Autokinetics selected the UQM PowerPhase75 and the hub-mounted configuration as the mainstream approach. Motors and controllers were ordered from UQM and delivered during this reporting period.

The rear suspension design was adjusted to accommodate the increased length of the UQM motor. This required modifications to the upper and lower control arm as well as the knuckle designs. The modified rear suspension corner is shown with the new motor in Figure 9.

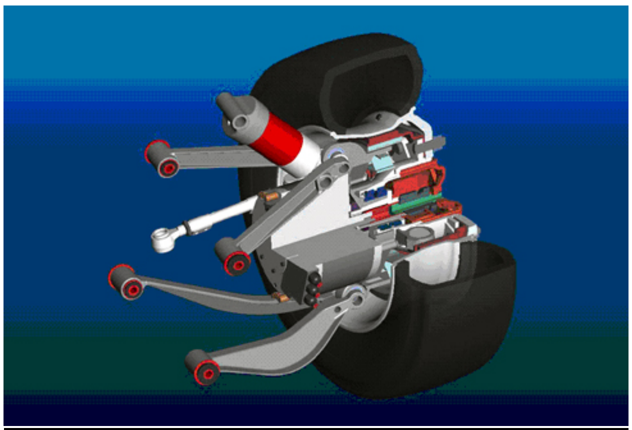

Figure 9. Rear suspension with UQM motor.

Dissemination and Commercialization

10/21/03—Meeting with Advanced Transportation Technology Institute (ATTI). Attended by Phil Sklad, Dick Ziegler, Richard Smith, (ORNL) and John Powell (ATTI).

11/18/03—Emmons attended DOE workshop "Tooling Technology – Low Volume Vehicle Production."

12/05/03—Presentation to DOE: Entrepreneur John Friedl's business plan to manufacture commercial vehicles using Autokinetics' structure technology.

3/10/04—Meeting with Transportation Design and Manufacturing Co. A discussion of hybrid systems integration was attended by Doug Mann and Greg Vanover.

3/04/04—Meeting with Ricardo, Inc. Louis Infante (V.P., vehicle engineering) attended an introduction to the technology. Infante reviewed structural issues with a current project and expressed interest in the technology.

3/19/04—Meeting with Ricardo. Follow-up meeting attended by Mick Winship and Abhay Bhivare.

4/13/04—UQM press release announced UQM's participation in the project. This statement was subsequently posted on the FreedomCAR website at http://www.eere.energy.gov/vehiclesandfuels/news/fcvt_news_042004.shtml

5/06/04—Meeting with IBIS Associates to initiate information gathering for its cost analysis. Attended by Tony Mascrin (IBIS) and Phil Sklad (ORNL).

6/10/04—Commercialization discussion (under non-disclosure agreement).

6/15/04—Commercialization discussion (under non-disclosure agreement).

6/18/04—Emmons presented a project review at ORNL for Dr. Sidney Diamond (DOE).

9/28/04—Commercialization discussion (under non-disclosure agreement).

Conclusions

Autokinetics remains confident that high-strength stainless steel has the potential to achieve significant mass reductions of bus structures. The bus body structure is now nearly complete; most of the identified technical risk issues have been resolved, and only moderate mass gain has occurred compared with early predictions. Ongoing fabrication of the physical prototype has provided concrete mass numbers, and we now expect the actual mass reduction for the complete vehicle to be close to 50%.

It is also hoped that practical commercialization can be achieved in the not-too-distant future. Low capital investment and an ample knowledge base are key enablers for commercialization. Much has been learned thus far about processing and assembling the body structure, and many useful techniques have been developed. Given the relative ease of constructing this prototype within our own facility, it is quite apparent that capital requirements for commercializing this technology will be relatively small. It is anticipated this will be illustrated by the independent cost analysis commissioned by DOE.

B. Stainless Steel Bus Structure—Manufacturing Cost Analysis

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Contractor: IBIS Associates, Inc.
Contract No.: 4000030946

Objectives

- Provide the bus development program with manufacturing cost analysis and economic understanding to plan a technology and application development strategy.
- Assess the cost of conventional bus structure fabrication.
- Assess the cost of the proposed stainless steel structure.
- Explore the impact of key design and process assumptions.
- Characterize the potential commercial value of the concept.

Approach

- Collect data for scenario and process definition.
- Assemble defining part and process data
- Develop simulation model structure
- Conduct baseline and scenario analyses and comparisons

Accomplishments

- Collected data on conventional bus manufacturing and visited production facilities.
- Completed model development and scenario designs.
- Presented side-by-side cost comparison of stainless steel concept to incumbent practice.
- Analyzed sensitivities to annual production volume, throughput, assembly time, etc.
- Assessed capital requirements, purchase facility investment, and scale-up schedule.

Future Direction

- Modify analyses to account for floor, skin, and roof. These are integral to the stainless steel bus concept but not part of the conventional bus structure. Including them will further improve the side-by-side economics

- Assess the impact of powertrain and interior systems.
- Analyze life-cycle and usage costs in terms of fuel, operation, and maintenance costs.

Introduction

DOE, in conjunction with Autokinetics, is pursuing a design and process technology development program for alternative metropolitan bus structure manufacturing. Central to the effort is the stainless steel roll-formed design concepts developed by Autokinetics. Key to the success of this program is a demonstration of commercial viability: reduced piece cost, lower capital investment, or improved lifecycle economics relative to incumbent practices. Based on process and design scenario information provided to IBIS from the DOE/ Autokinetics team, IBIS has evaluated the alternative design concepts for these structures and provided an analysis of manufacturing economics. This analysis seeks to quantify the commercial production economics of the design and production techniques developed by Autokinetics relative to incumbent practices for conventional bus manufacturing.

Bus Structure Scenarios

The basis for comparison of the conventional bus structure to the stainless steel concept is a 40-ft, low-floor metropolitan transit bus.

In summary, the stainless steel concept involves a floor and roof composed of three-layer panels made from welded outer skins and a corrugated, roll-formed core. Roll-formed pillars, rails, and sills complete the skeletal structure. Wheel wells and front and rear cap assemblies are welded from brake or press formings. The structure is assembled using spot welding.

Conventional manufacturing involves labor-intensive arc welding of tube stock. Sides, floors, roofs, and front and rear end units are made separately in subassembly cells on semi-dedicated fixtures (which can be modified for bus length). After final structure assembly, the frame is subjected to grit blasting and a zinc phosphate coating.

Model Development

Existing models of automotive body-in-white manufacturing were used as the starting point for the bus structure technical cost model. This format has the capability to efficiently track the high piece count of individual components involved. IBIS collected additional roll-forming process data and specific stainless steel alloy material properties to update earlier information already in possession. The assembly operations, specifically the custom-designed panel fabrication, were defined in terms of commercial production-rate equipment.

Separate model structures were constructed for conventional and roll-formed designs. Conventional manufacturing, relying principally on purchased tube stock, is modeled as a series of assembly cells. It accounts for material cost as the total of purchased components for each subassembly. A roll-formed structure, on the other hand, is modeled on the basis of each roll forming, with a major assembly operation into a unitized structure.

Data Collection

Data used in the technical cost models were collected through interviews and site visits with many sources, principally existing transit bus and motor coach manufacturers. These include New Flyer, Advanced Bus Industries, North American Bus Industries, Gillis, Orion, and Motor Coach Industries. Equipment manufacturers and municipal transit authorities also provided useful information. Autokinetics provided design information for the stainless steel concept.

Analyses

For comparison and simulation manageability, operations for each scenario were grouped as shown in Figures 1 and 2. The resulting cost comparison and sensitivities are shown in Figures 3 and 4.

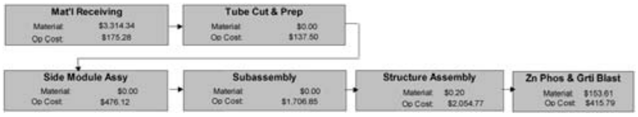

Figure 1. Conventional process flow.

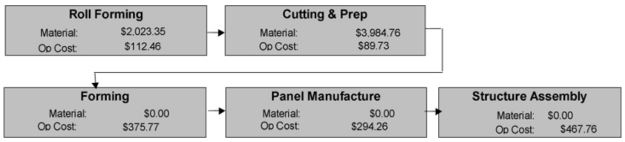

Figure 2. Stainless steel concept flow.

COST SUMMARY BY OPERATION	$/part Conventional	$/part Stainless	
Total Material	$3,468.15	$6,008.11	Total Material
Mat'l Receiving	$175.28	$112.46	Roll Forming
Tube Cut & Prep	$137.50	$89.73	Cutting & Prep
Side Module Assy	$476.12	$375.77	Forming
Subassembly	$1,706.85	$294.26	Panel Manufacture
Structure Assembly	$2,054.77	$467.76	Structure Assembly
Zn Phos & Grti Blast	$415.79		
TOTAL MFG COST	$8,434.47	$7,348.08	

Figure 3. Cost comparison table.

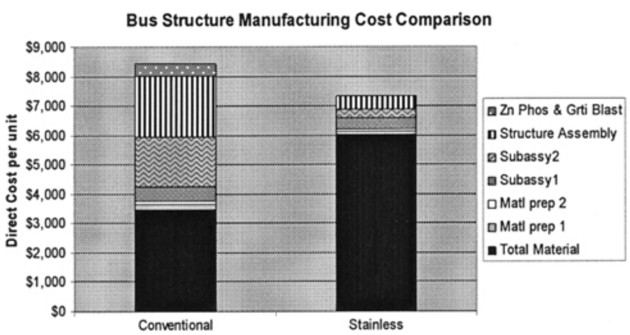

Figure 4. Cost comparison chart.

Conclusions

In addition to the weight savings gained from the stainless steel design (current numbers show approximately 1000 lb, not including additional savings of hundreds of pounds of flooring, skins, and roof already integral to the structure), the manufacturing economics of the stainless steel design are compelling. The combination of the novel design approach, using roll forming and high-rate spot welding (instead of arc welding), allows for a reduction in assembly labor and fixturing to offset the much greater material price of stainless steel relative to the steel tube stock.

As the program moves into the next phase of demonstrating a working powertrain, the extended benefits of the lightweight structure on reduced power requirements and secondary mass savings can be explored. The economic analysis can also be employed to demonstrate to potential manufacturers the specific capital requirements needed for commercializing the proposed concept.

C. Side Impact Analysis of a Lightweight Stainless Steel Bus Structure

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Contractor: Oak Ridge National Laboratory
Contract No.: DE-AC05-00OR22725

Objective

- Model and assess the structural performance of a lightweight stainless steel bus structure (LSSBS) during a side impact by a sport utility vehicle (SUV).

Approach

- Conduct the impact analysis simulation using finite element method (FEM) computer analysis.
- Develop a detailed model of a central five-column-long section of the LSSBS to model the area of collision, with two semi-rigid components on each end of the deformable section representing the remainder of the bus.
- Simulate a side impact collision scenario using LS-DYNA on supercomputers at the Oak Ridge National Laboratory Center for Computational Sciences.

Accomplishments

- Developed the detailed model of the center section of the LSSBS, including key structural features of the bus relevant to the side impact. The simulations showed overall satisfactory structural response.

Future Direction

- Use the results of the study to modify the bus design to reduce the damage and intrusion resulting from the collision and analyze the design modifications using the same approach.

Introduction

The ultralight stainless steel urban bus concept was developed by Autokinetics, Inc.[1] with the objective of demonstrating the feasibility of a stainless steel structural design for weight reduction in mass-transit vehicles. The resulting bus employs high-strength stainless steels and monocoque design to simultaneously achieve the weight reduction and maintain or surpass the performance of conventional bus designs. The bus body structure is shown in Figure 1.

Bus performance with respect to torsional and flexural rigidities and axial impact has been investigated using computational models. However, side-impact response has not been fully addressed yet; it is the subject of this research. A collision scenario that is considered to be a good measure of the side-impact performance of the bus is an impact of a mid-size SUV-class vehicle into the half span of

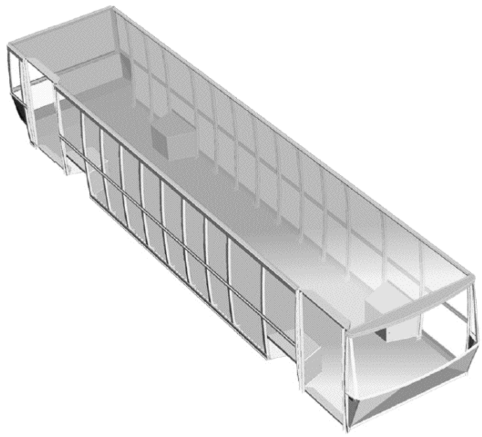

Figure 1. Ultralight stainless steel bus structure.

the bus. SUVs usually have a high ground clearance, and an SUV chassis may not coincide in height with the bus floor. In the case of the current design, it would obviously be desirable to transfer the impact loads into the rigid floor as efficiently as possible without allowing for a significant intrusion into the bus passenger space. The other essential structural component that comes directly into contact with the impacting vehicle is the lower reinforcement rail. This rail is supposed to distribute the impact force between the neighboring pillars. The bus floor and, to a lesser extent, the roof are the final destinations of the SUV impact load. In order to achieve a controlled load transfer into the floor and roof, it is necessary to maintain reasonable stability of the pillars and the reinforcement rail. Joints connecting pillars into the floor/roof must distribute the load very quickly without creating local instabilities or joint failure. Figure 2 shows the pillar joint with the roof.

Location, geometry, and bonding of the joint brackets are important for local load transfer; therefore, it is necessary to model them in sufficient detail to determine the local stability of the connection. Detailed computational models have been developed to adequately address these issues and provide a basis for further performance investigations that require high-resolution, nonlinear FEM analysis.

Development of the FEM Model

The finite element model of the bus structure involves several steps. The basic geometry of the

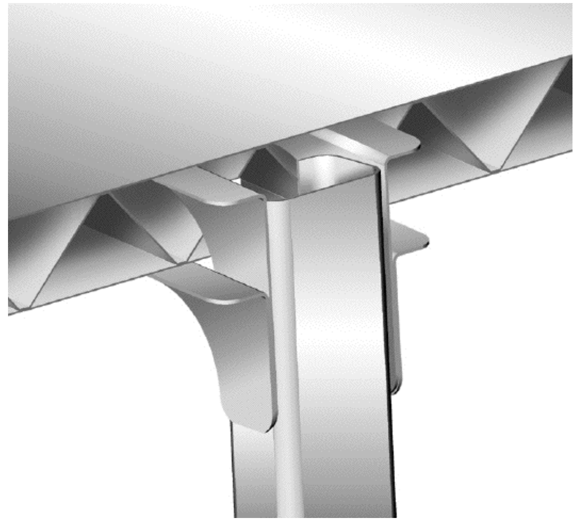

Figure 2. Pillar joint detail.

bus was provided by Autokinetics in the IGES format. The geometry data are used to generate surfaces that are used as projection targets for the FEM mesh generation. The data were provided for a single typical section ('segment') of the structure; Figure 3 shows the segment model. Repeated reflections and translations are used for the generation of the model used in the analysis.

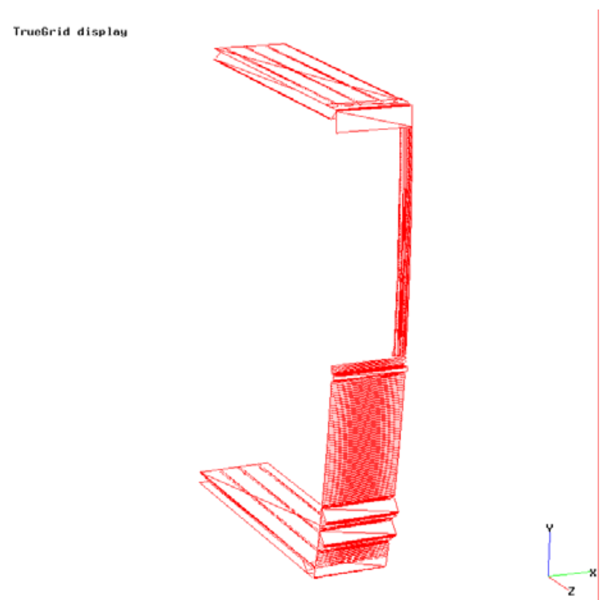

Figure 3. ViewPoint surfaces of bus 'segment' model.

The integrity of the body structure is provided almost exclusively by spot welds. Therefore, in order to create a realistic model for side impact it was essential to include them in the model. The location of the spot welds was provided in IGES format. A graphical representation of this data is shown in Figure 4.

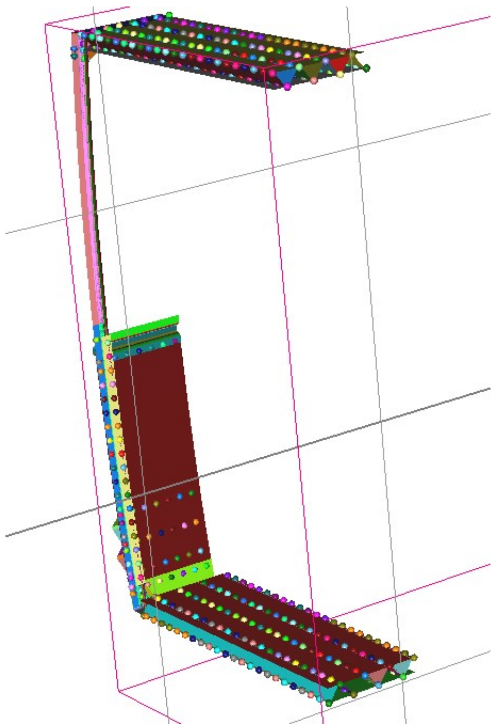

Figure 4. Spot welds in the bus segment.

The FEM model was developed using the spot weld locations as key locations for the mesh generation so that the locations of the spot welds exactly match the locations specified in the IGES geometry. The developed FEM model for the ten base segments, where spot weld locations are denoted by black dots, is shown in Figure 5.

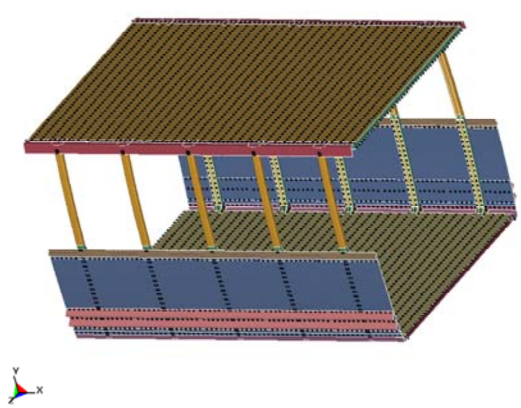

Figure 5. FEM model; black dots denote locations of spot welds.

FEM Simulations of Side Impact

The FEM model of the bus consists of a representative section and approximations of the front and rear of the bus. The approximate parts are modeled as stiff, elastic materials that approximate the areas of the bus that are not going to deform in the impact and provide vertical support relative to the ground of the bus assembly. Ideally, the actual bus geometry could have been modeled, but it was not available at the time of model creation.

Figure 6 shows the entire analysis model of the bus used in the analysis. This model has 287680 nodal points, 280148 shell elements, and 34567 beam elements.

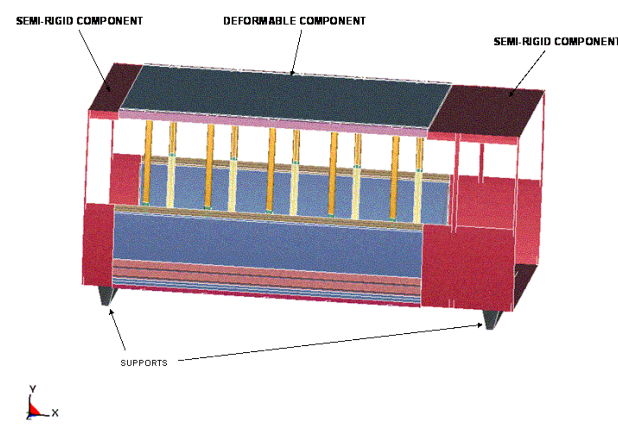

Figure 6. Finite element model of the LSSBS concept.

The FEM model used in the study of the side impact analysis includes a 'bullet' vehicle. For this analysis, the bullet vehicle is an 1998 Explorer SUV.[2] The representation of the merged bus-Explorer model is shown in Figure 7. Two cases have been considered for the impact analysis: the first one considers the case when the center (across the width) of the SUV engages the bus at a pillar location, and the second case considers the case when the center of the SUV engages the bus at the midpoint between pillars. Figure 7 shows the model of the first case.

The combined model has 427675 nodal points, 281102 hexahedral elements, 414942 shell elements, 280677 beam elements, and 8653 spot welds.

The analysis considers the impact of the SUV traveling at 25 mph at the time of engagement with

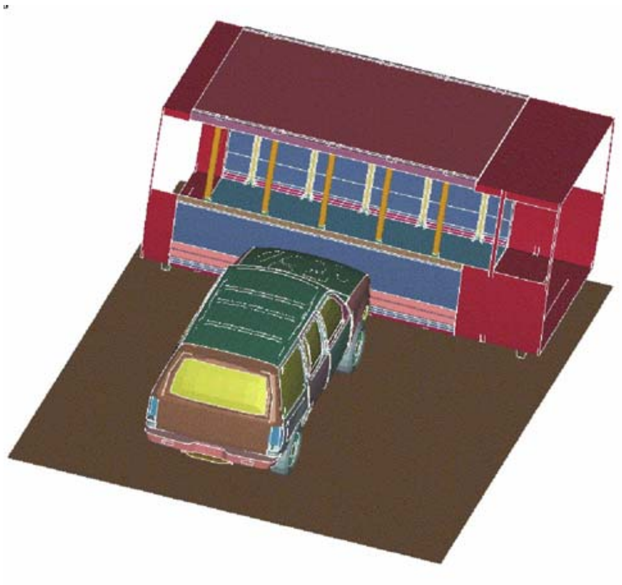

Figure 7. Finite element model for the SUV-LSSBS impact at column.

the stationary bus. The analysis has been performed using the computer program LS-DYNA.[3]

The following paragraphs discuss the results of the analysis performed to assess the bus integrity when the SUV traveling at 25 mph impacts the bus so that the center of the SUV is between the two bus pillars.

The configuration of the model at a time when the elastic deformation of the bus reaches a condition of quasi-steady state is shown in Figure 8. At this point in the analysis, the SUV–LSSBS assembly moves as a rigid body, and very little relative deformation is imposed upon the bus structure beyond the end time of the analysis.

The intrusion into the bus body, defined as the reduction in width between the outward pillar and the corresponding pillar near the point of impact, was calculated. Two locations along the height of the pillar were chosen for the determination of this parameter: at the vertical level that corresponds to the bumper height of the bullet vehicle, and at the sill level of the bus window opening. Figure 9 shows the time history of these intrusion measurements. The top curve corresponds to the bumper height location; the lower curve corresponds to the sill location. Final intrusion values are 195 mm and 145 mm at the bumper height and sill level locations, respectively.

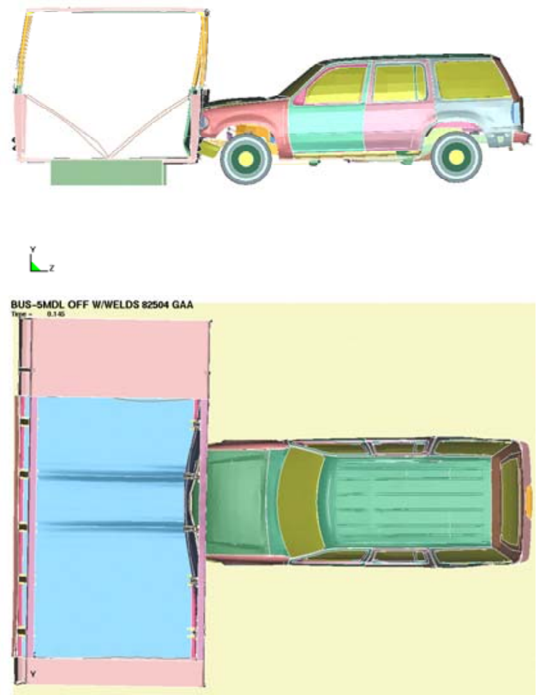

Figure 8. Side view (top) and top view with roof panels removed (bottom) of model configuration at end of simulation.

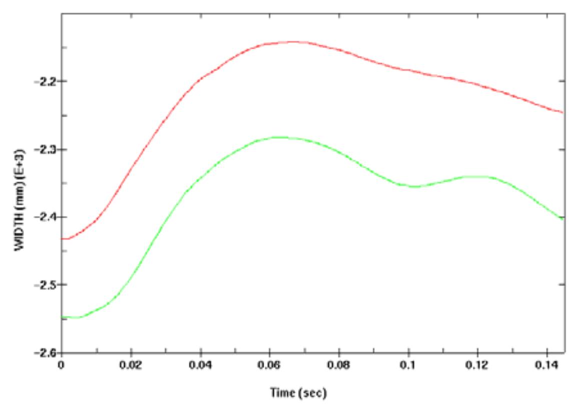

Figure 9. Width measured between columns at center column line.

The integrity of the bus structure can be evaluated in terms of the ability of the brackets to maintain the connection between the floor assembly and the lower pillar sections. Failure of the spot welds at the bracket interface between the floor plates and the lower section of the pillar compromises the integrity of the structure, as most of the stiffness of the assembly depends on the integrity of the side components. The analysis shows that the lower row of spot welds can fail in the vertical leg of the top brackets that connect to the pillar. The analysis also shows that the connection between the horizontal legs of the bracket that connects to the top floor plate undergoes relatively large deformation. This is attributed to the topology of the spot welds at this interface; only the inner part of the horizontal part of the bracket is attached to the floor plate. The result is a cantilever mode of deformation for the bracket. Potential improvement in the performance of the structure could be achieved if additional reinforcement were provided between the horizontal section of the lower bracket and the floor rail and between the horizontal section of the top bracket and the roof rail. Another possible design modification is reinforcement of the pillar. The corresponding design modifications will be addressed in the continuation of the study.

Conclusions

We have developed an FEM model for the structural analysis of a side impact against a LSSBS.

Results of the study point to areas that may warrant some design modifications in order to reduce the damage and the intrusion of the SUV into the LSSBS. The model can be further refined to allow for more accurate simulation and flexibility for modeling of different loading situations.

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2. G. Aramayo, "Parametric Finite Element Model of a Sport Utility Vehicle: Development and Validation, in *Proceedings of the 7th International LS-DYNA Users Conference*, Dearborn, MI, 2002.

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D. New-Generation Frame for Pickup/Sport Utility Vehicle Application

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Contractor: Pacific Northwest National Laboratory
Contract No. DE-AC06-76RLO 1830

Objective

- Evaluate the design of an optimized hybrid materials frame that represents a new generation of pickup/sport utility vehicle (PU/SUV) frame applications and vehicle architecture.

Approach

- Apply high-risk manufacturing and design methods to the PU/SUV frame to reduce mass while meeting cost goals consistent with a high-production vehicle.

Accomplishments

- Established performance, packaging, and weight targets for the second iteration of the new-generation frame, “the next-generation frame” (NGF).
- Created a design for the NGF that projects a greater weight reduction and a decrease in the number of parts compared with the current steel baseline frame.
- Created a computer-aided engineering (CAE) model of the NGF to evaluate impact; noise, vibration, and harshness (NVH); and durability.
- Completed CAE and design iterations to meet impact, NVH, and durability requirements.
- Successfully demonstrated the “5-star” crash rating.
- Established a preliminary cost estimate for frame production and prototyping.
- Established initial cost estimates for the frame that are 12% higher than the current frame with a 200-lb weight savings. The initial cost projections are favorable and are being evaluated in more detail.

Future Direction

- Construct the full NGF frame and perform vehicle testing to validate the CAE-designed NGF.
- Complete prototype frame component design and procure parts for DCX assembly.
- Validate the CAE analysis by DCX in a full-frame test to be determined by identifying needs from CAE testing.

Introduction

Increased consumer demand for PUs/SUVs has resulted in increased fleet fuel consumption, and the trend toward consumer demand for PUs/SUVs has been predicted to increase. By 2005 the fuel demand for this class of vehicle will exceed that for passenger automobiles.[1, 2] The objective of this project is to explore manufacturing methods and materials to reduce the mass of the SUV/PU frame, thereby reducing fuel consumption for this class of vehicle.

During the second quarter of FY 2003, DaimlerChrysler completed vehicle testing at the DCX Proving Grounds using an SUV/PU platform equipped with a hybrid frame. Results of the accelerated testing have proved that (1) the hybrid frame design had sufficient strength and durability to meet the vehicle performance requirements, and (2) the frame was probably somewhat overbuilt and heavier than required, even with a substantial weight savings over the current baseline steel frame.

The next phase of the project will evaluate the use of a lighter frame, the NGF (Figure 1). The NGF uses a CAE approach and higher-risk manufacturing technologies. The projected weight for the NGF is less than that for the previously tested new-generation frame, and it requires 35% fewer components.

Approach

A CAE model of the NGF was created and design iterations were performed to meet the NVH, impact, and durability requirements for a DCX 5-star rating. A prototype of the frame will be fabricated and evaluated by frame flexure and road tests.

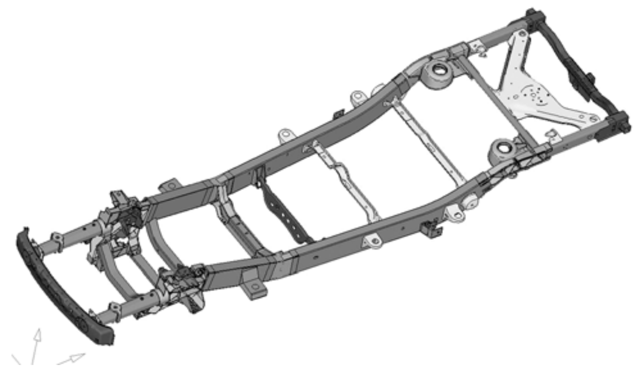

Figure 1. Next-generation frame design.

Progress

CAE analyses of the frame are completed and have satisfied all requirements for impact, NVH, and durability analyses. Owing to the large section height of the aluminum extrusions, intrusion into the passenger compartment during impact analysis proved to be the most challenging problem.

Complete CAE impact analyses (like those shown in Figure 2) have been reiterated upon and reduced the intrusion into an acceptable range. A full 5-star rating has been attained with only minor frame modifications. Intrusion into the vehicle is measured in terms of the maximum displacement of the vehicle into the passenger compartment. The 5-star rating is achieved when all intrusion values are below a “good” rating as determined by DCX safety review. Reiteration on the original NGF design has resulted in all values below the “good” rating, as shown in Figure 3.

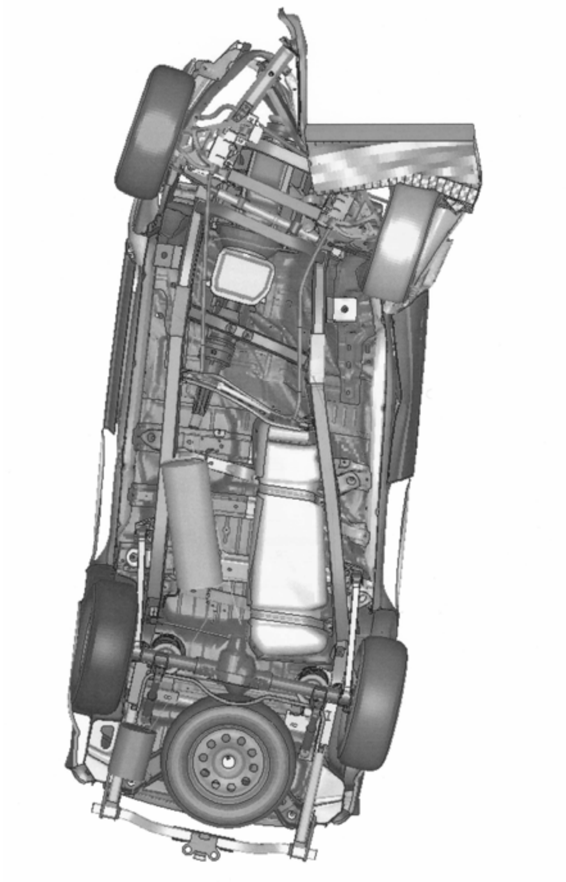

Figure 2. Frontal impact analysis of the NGF.

The aluminum frame complicates the design for intrusion because of the increased section size. The aluminum extrusions are 5 cm taller than the steel frame sections. In order to have an equivalent intrusion, the NGF must be designed not to deflect as much as the steel version. The actual magnitude of deflection at each passenger compartment location, shown in Figure 3, indicates that the additional 5 cm of frame height reduces the allowable deflection of the frame by approximately 30% in locations where a total intrusion of 15 cm is allowed.

The design of the frame has been completed, and a bill of materials (BOM) has been created and used for prototype and future production cost quota

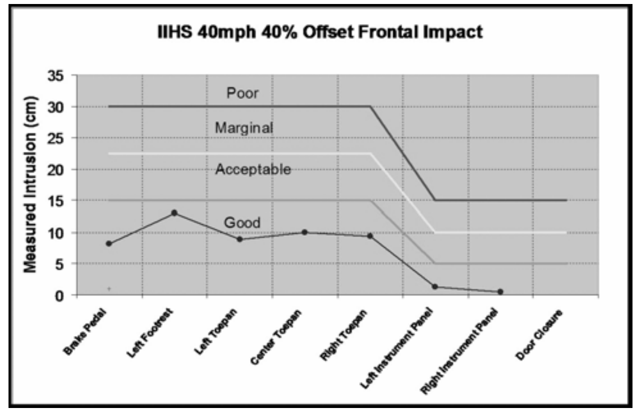

Figure 3. Intrusion measurements for 40% offset frontal impact for the NGF.

tions. Initial cost analysis shows that a 200-lb savings can be achieved with a 12% cost penalty. Additional analyses of cost and re-design for production will be performed.

Future Direction

The CAE/design for the NGF is complete, a BOM has been created, and a suitable frame that shows a weight savings of 200 lb has been proposed. The next step in the frame project will be validation of the CAE results through full-scale vehicle testing and frame flexure tests. A prototype frame will be fabricated, and flexure will be tested by twisting. After flexure testing, the full-scale frame will be assembled into a DCX vehicle platform and evaluated on the test track for durability and driver-felt comfort and performance.

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E. Lightweight Trailer—Liburndas Project

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Contractor: Heil Trailer International
Contract No.: 4000027094

Objective

- Reduce the net weight of an aluminum tank semi-trailer by 20% by using a cylindrical design and assimilating available composite technology for functional components.

Approach

- Develop a new frameless vessel design incorporating a new cross-section, flangeless heads, and internal rings.
- Optimize design through finite element analysis (FEA) and testing.
- Explore existing composite accessories.
- Conduct a focus group and a marketing study, including a campaign for the new design.
- Complete a manufacturing study, including a labor rate analysis.
- Manufacture and test prototype.

Accomplishments

- Completed vessel and bogie (run gear suspension frame) design.
- Completed FEA of vessel and bogie.
- Completed evaluation of friction stir welding samples.
- Completed initial testing of flangeless, dishless head design.
- Defined and approved loading head parameters.
- Completed focus group.
- Started marketing and manufacturing study.

Future Direction

- Complete fifth-wheel design and FEA.
- Complete accessory design and FEA.
- Validate possible composite accessories.
- Complete manufacturing study and marketing report.
- Manufacture prototype and conduct track test.
- Conduct marketing and sales campaign.

Introduction

The Liburndas Project is Heil Trailer International's effort to design and build an aluminum semi-trailer for petroleum products that is lighter, stronger, and safer than any before it. By using a cylindrical cross section and assimilating composites into select trailer components, Heil's Research and Development (R&D) Group proposes to reduce the aluminum tank semi-trailer's net weight by 20 %.

Just changing the geometry of the vessel by redesigning it to a cylindrical shape will allow a reduction in shell thickness and elimination of historical strengthening structures that have plagued equipment with parasitic mass. This new design will also lower the center of gravity (CG) by 25–30%, which enhances the safety of the trailer with respect to roll-over potential (see Figure 1).

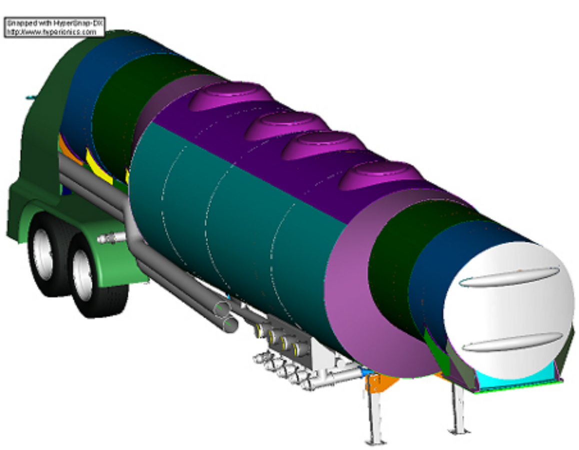

Figure 1. New concept petroleum trailer.

Investigating a new aluminum alloy for weight reduction in areas not regulated by the U.S. Department of Transportation (DOT) is an objective of the project as well. Areas such as the frame rails for the suspension and fifth-wheel plate are valid candidates. Although some weight savings is possible, this is secondary to the contributions the new cylindrical design and composite accessories will make to Heil's overall weight reduction goals.

Accessories made from composites are critical to meeting weight reduction goals and will ultimately reduce the mass of the trailer and improve corrosion resistance. This project's purpose is not to create or test a new composite for these areas. Existing composites will be explored that have proved successful in the market. Areas that are likely candidates for composites are fenders, cabinets, hose holders, ladders, and suspension support structures.

Although a successful vessel design and notable composite integration will result in reaching weight reduction goals, it is paramount to the project's success that the market accept the new design. Because of the competitive nature of the market, data will be collected covertly, without divulging the new trailer's design or benefit. Therefore, the marketing study initially will determine acceptable envelopes for piping and discharge outlets, as well as conduct a preliminary commercial viability study based on the design's limits and/or restraints. A marketing campaign to bolster product acceptance will take place near the end of the project. The initial marketing study began during Phase 1 of the project and should be completed before the first prototype is built. The marketing campaign will take place during Phase 3 (after the successful field testing of the second prototype) and should result in orders for production models.

A successful product resulting from this project would allow carriers to safely deliver 2000–2500 lb more payload per trip**,** ultimately reducing the daily average number of miles required to deliver product by about 1%. On a national level (the current population of petroleum tank trailers is approximately 50,000 units), this could equate to over 200,000 miles per year saved, or 30,000 gallons of fuel per year.

Vessel Design

Cross Section

An important part of Heil's new design concept for its petroleum trailer is the cross section of the vessel. In today's petroleum trailers, the most common cross section used is an elliptical shape, used to lower the overall height and center of gravity of the trailer. Since petroleum trailers are not unloaded or loaded with pressure, the elliptical shape works well.

When the structure of a petroleum trailer's vessel is studied, it is simply analyzed as a supported beam with reactions at the suspension and kingpin plate. This condition places the bottom of the trailer vessel in tension and the top in compression. The advantage of a round cross section under these loads is that the radius of the top is tighter or smaller and therefore more resistant to buckling under the compression loads. This allows the shell thickness of the vessel to be thinned, compared with an elliptical cross section, and thus saves weight and material.

Even though petroleum trailers are not pressurized, they do occasionally see some low vacuum or pressure differentials during loading and unloading. Today's trailers are equipped with vents to prevent damage to the vessel if this condition becomes excessive. In the event of a vent failure, a round vessel is more likely to survive a pressure or vacuum overload, whereas an elliptical vessel will tend to fail.

A round vessel is therefore stronger, lighter, safer, and more stable than an elliptical vessel for an equivalent cross sectional area. The only advantage of an elliptical trailer is its overall lower height and center of gravity. Designing a round vessel with a drop center can offset this advantage (Figure 2).

Drop Center Design

Dropping the center of the vessel in relation to the front and rear not only lowers the center of gravity but also causes the lateral center of mass to stay near the longitudinal center of the trailer, as shown in Figure 3.

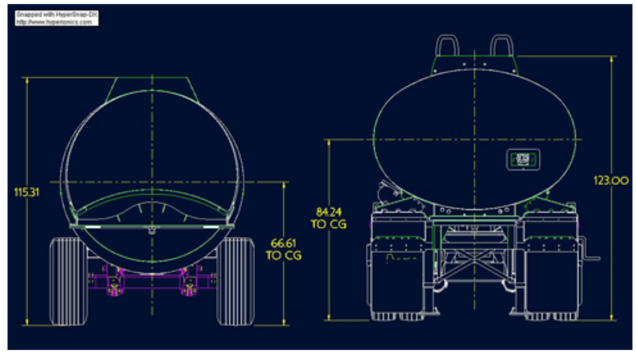

Figure 2. Height and center of gravity comparison.

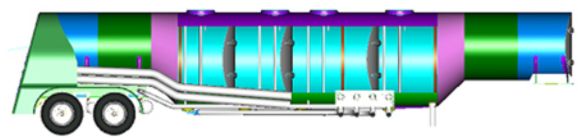

Figure 3. Drop center design.

Federal weight laws call for manufacturers to design trailers with equal loads on the tractor's drive axles and the trailer's suspension. By designing a lower front *and* rear end section of the vessel, we can engineer the trailer so that the mass is equally distributed over the rear of the trailer (bogie) and the tractor's rear axles.

Elimination of Surge Heads

Petroleum tank trailers are designed to DOT 406 specifications as found in the Code of Federal Regulations Title 49. Section 178.345-7 of this code discusses circumferential reinforcements in trailers and mandates that the maximum unreinforced portion of the vessel's shell not exceed 60 in. Traditionally, this has been accomplished in petroleum trailers through the use of surge heads or baffles. These surge baffles are the same heads that separate the trailer's compartments, but they have holes formed in them to allow product to flow through them. These surge baffles help with the surge of the product during acceleration and deceleration and serve as the circumferential reinforcements.

Replacing these surge baffles with an adequately designed internal ring can achieve a considerable weight savings. However, rings will not help with product surge, and drivers will have to be trained to handle the "feel" of the tank in certain road conditions. The market's opinion (business owners and drivers) on internal rings and their advantages and disadvantages will be one of the topics for the focus group and marketing study.

Liquid trailers without surge baffles are not uncommon in the chemical and food industry, where the cleanability of the inside of the trailer is important. Drivers in these industries have learned to drive safely without baffles; therefore, it is anticipated that the weight benefits will outweigh the surge issue. It should also be noted that there is no product surge when a trailer is completely full or empty.

Flangeless, Dishless Heads

A new concept with regard to the vessel design is being applied to the Liburndas Project. This is a redesign of the compartment heads that separate different commodities in a petroleum trailer. These heads are typically dished and flanged bulkheads that are connected to the shell via a single fillet weld. The Liburndas vessel will use a flangeless, dishless head, which will be connected to the shell via two fillet welds. A Pro-E model of the head is depicted in Figure 4.

Figure 4. Flangeless head concept.

The Liburndas vessel is a perfect application for the flangeless head—it is lighter, the welds are stronger, the strength is comparable, and the manufacturability is more precise than for the current style head. The flangeless head is much easier to manufacture and should offset part of the cost of the composites. One of the goals of marketing goals is to ensure that the R&D group's new design—lighter, stronger, and more stable—does not cost more than the market will bear for those benefits. This offset strategy should keep the price of the new design within acceptable limits for the market.

Heil has been working on forming techniques for this new head with the Alcoa Technical Center and has already conducted preliminary testing of a "simulated" prototype head at its Athens, Tennessee, R&D facility. The prototype head can be seen in Figure 5. Initial testing was promising, and advanced prototypes are planned for continued testing.

Figure 5. Flangeless head test vessel.

Framing

The final design and FEA of the bogie frame has been successfully completed. It eliminated some framing requirements (and weight) for both bogie and vessel structure mounting compared with current framing designs. The Liburndas bogie design can be seen in Figure 6 below.

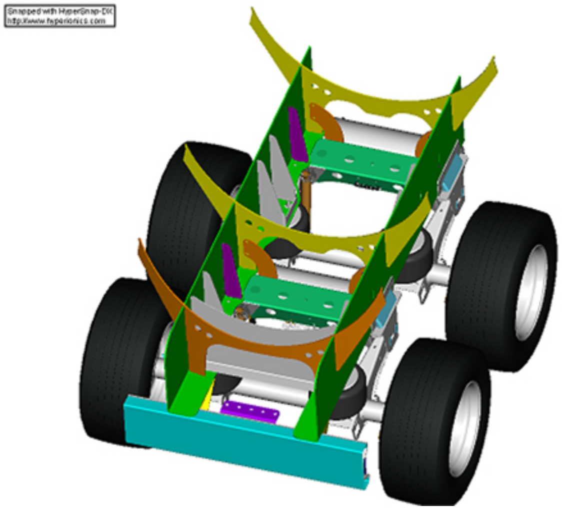

Figure 6. Liburndas bogie frame.

The bogie frame is one of the most critical design areas for a petroleum trailer. The vessel experiences not only loads from the force of gravity acting on the payload but also loads due to articulation or twisting as it maneuvers over the road around corners. Consequently, a leak due to weld fatigue would most likely occur in this area. To simulate road conditions, FEA on the frame was completed for four load cases: (1) 2-G downward, vertical inertial; (2) 2-G forward, horizontal inertial; (3) 1-G lateral, horizontal inertial (10-ton axle load traveling around curves); and (4) 1-G lateral horizontal inertial load (turning on the spot).

The initial analysis indicated that the mild steel crossmember structure gave cause for concern with unacceptable stress levels under the load cases specified. However, the initial FEA model did not take into account the link of the top crossmember to the frame or the correct welding techniques. After further review and FEA remodeling, the bogie frame design actually experienced acceptable stress levels. To confirm our results, the bogie frame design was also tested by Hendrickson, the air ride suspension manufacturer. Hendrickson conducted similar FEA modeling and confirmed our final test results.

Overturn Rails/Vapor Manifold

Finally, the vessel design will eliminate the need for overturn rails on the top of the trailer. The overturn rails act as guards to prevent a manhole from opening during a rollover situation. The flashing rails also act as a manifold for vapor collection and recovery during the loading and unloading of a trailer. A significant amount of weight can be saved by the successful elimination of the rails. It can be done with the installation of recessed manholes, which are widely used in Europe (see Figure 7).

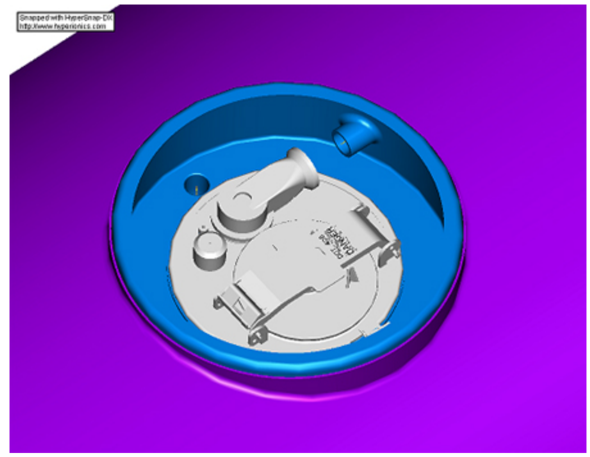

Figure 7. Recessed manhole.

Vapor collection and recovery will be completed using internal vapor lines that drop down through each compartment from the manholes. Lines will be manifolded outside and under the vessel. This configuration has been successfully designed and tested by Heil in Europe. Its application to the Liburndas vessel will save approximately 400 lb, the weight of both flashing rails.

Vessel Weight Reduction

To date, the total weight reduction goals are as follows: from the shell, 15%; from the heads, 20%; by eliminating the overturn/flashing rails, 20%. The remaining 45% will come from the framing and accessories design.

<u>Friction Stir Welding</u>

During the project, Heil is also working closely with Oak Ridge National Laboratory to determine the feasibility of applying friction stir welding (FSW) to the manufacturing process for the Liburndas vessel. The most likely area will be the large, flat aluminum sheets that make up the barrel proper (currently done on a plasma table). FSW samples have been collected, along with both gas tungsten arc and gas metal arc samples, and bend and tensile testing will begin this phase.

Marketing

Focus Group

Heil invited five customers representing a cross section of the industry (major oil companies, jobbers and common carriers) to participate in a focus group this past October. The customers in attendance were positive and encouraged by the information presented. They ranked their needs and wants as follows: first, the capability to haul more payload; second, better operational efficiency; finally, a design as safe as, if not safer than, than current trailers.

As anticipated, an increase in payload capability was the customer's number one requirement for the new design. If afforded the capability to haul more product, they can increase revenue on a per-load basis and reduce maintenance and operational expenses over the life of the trailer.

Although recessed manholes were not seen as an advantage to the customer, they would be "tolerated" if they created the weight savings advertised. Concerns exist over weather caps, internal drains, and internal vapor piping that would exist with the manholes.

The customer's operational and safety requirements may drive a redesign of the accessory location and possibly the vessel diameter. Currently, the Liburndas cabinet and accessories are located at the rear of the trailer, which would be unacceptable to the operators. It was determined during the focus group that the operators' perceptions of the new design will have an important bearing on the success of the Liburndas trailer in the market.

The low belly height was actually a concern because of the potential for side collisions, which was perceived to outweigh the advantages of a lower center of gravity. The trailer may perform better in a rollover situation, but it may be more susceptible to loss of load in a side impact collision. The customers in the focus group recommended we limit the amount of drop to 50% of the planned design and move the accessories to the side of the vessel. This would make the trailer operationally acceptable and still improve on the safety of the existing trailer in the market.

The project leader is considering reducing the major diameter and increasing the minor end tube diameters to maintain capacity and provide more room for accessories on the side of the trailer, the typical location for accessories in today's trailers.

Conclusions

Excellent progress has been made on the vessel and bogie design and FEA during the first year of the project. Design and FEA of the fifth-wheel plate are now on schedule and should be completed by the end of the month. All Phase 1 deliverables should be completed by the end of the year, according to the project schedule.

Continued study and testing will take place on the flangless head design. Once a die is acquired and actual test heads are constructed, mock-up prototype testing will be completed. It is anticipated that the flangeless head design will be very successful, which will accelerate the project into Phase 3—field testing of a prototype.

The marketing research completed to date reflects initial acceptance of the new design, with the exception of the existing accessory locations. Redesign of the accessories will take place quickly over the next month. Market acceptance of the cylindrical design, flangeless heads, and internal rings will make the Liburndas trailer a viable alternative to and inevitable replacement for the elliptical trailer. Once it is in the market, the popularity of the trailer is expected to increase exponentially because of its improved fuel delivery capabilities and roll stability.